FRACTIONATION OF Eu FROM OTHER REE BY MELT-ROCK REACTION IN THE LUNAR MANTLE.   Z. T. Morgan, Y. Liang, and P. C. Hess, Brown University, Dept. of Geological Sciences, Providence, RI 02912. (Zachary_T_Morgan@Brown.edu).

Introduction: As the lunar magma ocean (LMO) cooled it first crystallized Mg-rich olivine (ol) and orthopyroxene (opx). With continued cooling and crystallization the residual liquid in the LMO becomes enriched in FeO, TiO_2 and other incompatible elements [1]. Eventually the overlying melt will be denser than the underlying liquid interstitial to the cumulus crystals within the LMO. At some point the dense liquid will descend through the cumulate crystals modifying the compositions of the interstitial melt and cumulus minerals through dissolution-precipitation and diffusive change.   These crystal-melt exchange reactions may have important implications for the formation of a REE enriched source region while preserving its primitive major element signature (possibly the Mg suite source region). One of the unique features of melt flow and melt-rock reaction in the lunar mantle is the strong fractionation of Eu from other REE. As will be shown below, this can happen even in the absence of plagioclase.

Model: The chemical fractionations resulting from a descending melt through a porous harzburgite matrix can be illustrated using a 1D diffusion-advection-reaction model, similar to those used to study metasomatism within the Earth's mantle [2,3]. Variations in FeO, MgO, CaO and the REE in the melt, and in ol and opx as a function of time and distance within the harzburgite were calculated using a finite difference method. For purpose of illustration we use the 95% crystallized LMO melt composition from Snyder et al. [1] as the starting composition for the descending melt [which can be read from Fig. 1 at $x = 0$ and curve (a) in Fig. 2]. The major element compositions of the interstitial melt in equilibrium with a high Mg# harzburgite crystallized from the LMO [which can be read from Fig. 1 at $x/l = 10$] were estimated using the MELTS program [1, 4]. The initial melt in equilibrium with the harzburgite has a chondritic REE composition [curve (e) in Fig. 2]. For simplicity we assume a constant melt percolation velocity of 0.1 m/yr and a constant melt porosity of 4%. The proportions of opx (10-90%) were fixed in a given simulation. Effects of compaction and crystallization within the harzburgite matrix were also neglected. Partition coefficients (Kd) and diffusion coefficients in the melt and minerals were either from or estimated from the literature (see legend to Fig. 1 for details).

Results and Discussions: A series of numerical calculations were performed to explore the parameter space and their effects on major and trace element fractionation in the lunar mantle. Overall our simulations show that the transport of compatible elements, such as FeO and MgO, always lag behind the strongly incompatible elements (REE) at a given time. The highly incompatible REE descend much further than the compatible or moderately incompatible elements (Fig. 1). Figures 1, 2 and 3A show an example of our calculated major and trace element distributions in the interstitial melt and opx in the harzburgite matrix (ol:opx = 1:9) at a given time. Hence it is quite possible to strongly fractionate the major elements from the incompatible trace elements. This suggests the possibility of enriching deep lunar cumulates with the highly incompatible trace elements without significantly modifying their major element compositions, potentially forming the source region for the Mg suite rocks.

Reactive melt flow also plays an important role in determining the REE composition of the opx within the harzburgite. The small partition coefficients and the limited crystal-melt exchange rates will result in small fractionations among the LREE in the descending melt. The biggest effect can be seen in the more compatible HREE (Fig. 2). Moreover, because Eu^{2+} is more incompatible ($Kd_{Eu} \sim 0.5Kd_{Sm}$ [5, 6]) and expected to diffuse faster than the other REE in opx ($D_{Eu} \sim 10D_{REE}$) the exchange rate of Eu^{2+} between the descending melt and opx becomes very important. The faster exchange rate will gradually remove the original negative Eu anomaly in the opx that is normally predicted from the equilibrium partition coefficient data [curve (a) in Fig. 3A]. This removal of the Eu anomaly has an important effect on any melts produced by partial melting of this opx-bearing matrix – the melt in equilibrium with the metasomatized opx will have a positive Eu anomaly as shown in Fig. 3B. It should be stressed that this positive Eu anomaly is the result of differences in the exchange rates and partition coefficients between the infiltrating melt and the opx for Eu^{2+} and the other REE^{3+}, not the involvement of plagioclase.

The mineralogy of the solid matrix also plays an important role in generating the Eu anomaly and decoupling of the compatible and incompatible elements. By varying the proportions of ol and opx in the harzburgite we can change the behavior of CaO from infiltrating nearly as fast as the REE (when harzburgite has 10% opx) to nearly the same rate as FeO and MgO (when harzburgite is 90% opx). If the descending melt percolates through any regions containing plagioclase,

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Eu will be further fractionated from the rest of the REE because Eu^{2+} is more compatible with the plagioclase. The initially small negative Eu anomaly such as the one shown in Fig. 2 will become increasingly large. Hence the positive Eu anomaly in Fig. 3 may not develop if the harzburgite is overlain by a layer of plagioclase mush.
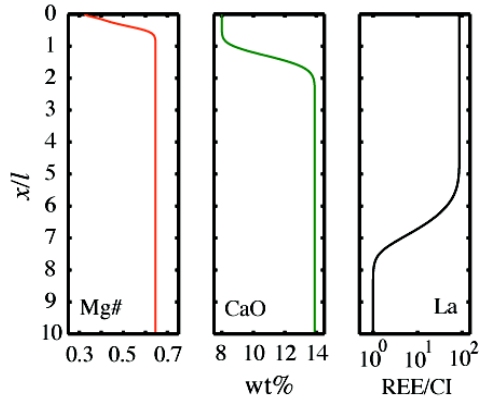

Fig. 1. Calculated major and trace element profiles in the melt as a function of normalized depth (x/l) within the harzburgite. If we assume a length scale of 10 km (for each unit of x/l) these profiles correspond to a time scale of 600,000 years. The Kds for FeO, MgO, and CaO in ol are from [7]. Kds for FeO, MgO, and CaO in opx were calculated using the ol and melt data. The Kds for REE in opx are from [5,6], and we assume the Kds for REE in ol to be 0.1*opx. The diffusion coefficients in the melt are from [8] for CaO, and [9] for FeO and MgO. The Eu^{2+} diffusivity in basalt is from [10] and we scale the other REE diffusivities to Eu^{2+} using [11]. Our opx diffusion coefficients for FeO and MgO are from [12] and we assume it is similar for CaO. We assume that Eu^{2+} diffuses at the same rate as Sr^{2+} [13] and that the REE diffusivities are 0.1*diopside diffusivities [14]. The cation diffusion coefficients in ol are from [15] for CaO, MgO and FeO and that REE diffusion coefficients are 0.1*opx.
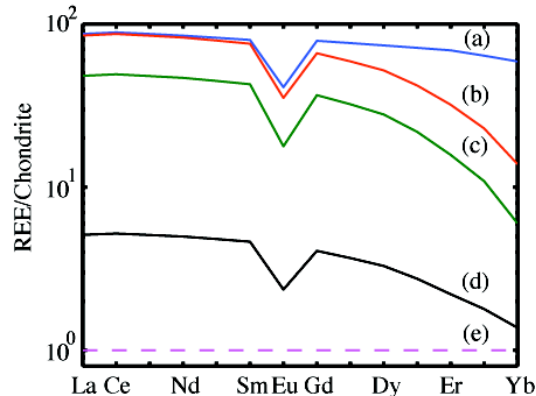

Fig. 2. Calculated REE patterns of the melt descending through the harzburgite at a given time and $x/l = 0$

(a), 5 (b), 6 (c), 7 (d), and 10 (e). Curve (a) corresponds to the initial composition of the descending melt, and (e) corresponds to the initial composition in equilibrium with the harzburgite.
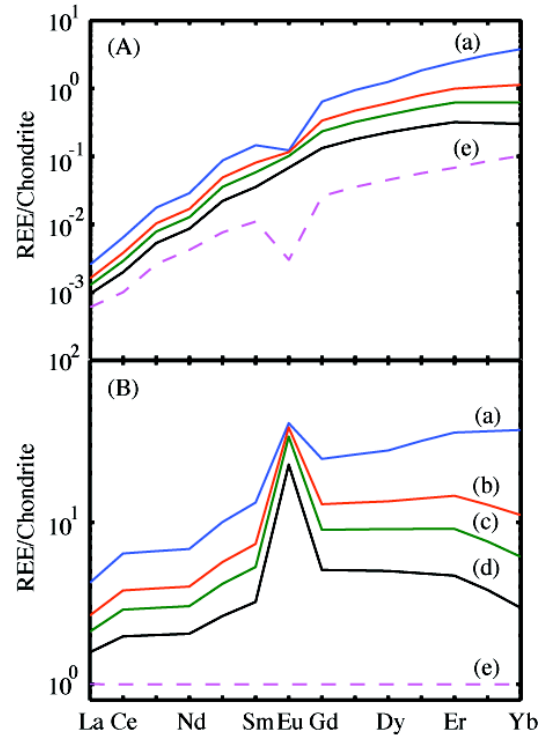

Fig. 3. (A) REE compositions of opx coexisting (but not in equilibrium) with the melts shown in Fig. 2 at a selected time [$x/l = 0$ (a), 3 (b), 4 (c), 5 (d), and 10 (e)]. (B) Calculated REE compositions of the melt that would be in equilibrium with the opx shown in (A) ($C_f = C_s/Kd$). Again the dashed line (e) corresponds to the initial composition of harzburgite.

References: [1] Snyder et al. (1992) *GCA, 56,* 3809-3823. [2] Navon O. and Stolper E. (1987) *J. Geol., 95,* 285-307. [3] Bodinier et al. (1990) *J. Petrol., 31,* 597-628. [4] Ghiorso M.S. and Sack R.O. (1995) *CMP, 119,* 197-212. [5] McKay et al. (1991) *LPSC XXII,* 883–884. [6] Papike et al. (1996) *GCA, 60,* 3967-3978. [7] Ford et al. (1983) *J. Petrol., 24,* 256-265. [8] Hofmann A.W. and Magaritz M. (1977) *J. Geophys. Res., 82,* 5432-5440. [9] Lowry et al. (1982) *CMP, 80,* 254-261. [10] Magaritz M. and Hofmann A. (1978) *GCA, 42,* 847-858. [11] Nakamura, E. and Kushiro I. (1998) *GCA, 62,* 3151-3160. [12] Ganguly, J. and Tazzoli, V. (1994) *Am. Mineral, 79,* 930–937. [14] Van Orman et al. (2001) *CMP, 141,* 687-703. [13] Sneeringer et al. (1984) *GCA, 48,* 1589-1608. [15] Jurewicz A.J.G. and Watson, E.B. (1988) *CMP, 99,* 186-201.